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Relativistic Gravity

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ABSTRACT

Recent astronomical discoveries -- quasars, pulsars, gravitational waves, cosmic microwave radiation -- reveal that relativistic gravitational effects are of great importance in our Universe. Unfortunately, we do not now have a firm experimental basis for deciding which relativistic theory of gravity is correct: Einstein's general relativity theory, the Brans-Dicke scalar-tensor theory, or some other theory. However, space technology will make possible a number of high-precision experimental tests in the next decade.

HISTORICAL BACKGROUND

Newton's law of gravity -- that each object in the Universe attracts every other object with a force which is proportional to the product of their masses, and inversely proportional to the square of their separation -- was one of the greatest triumphs of pre-twentieth century physics. It enabled one to explain completely and accurately the trajectories of objects shot into the air on earth, the motions of planets and their satellites in the solar system, and (very recently) the orbits of space craft. In addition, it is a crucial ingredient in our modern understanding of the structures and evolution of the earth, the sun, the stars, and the Galaxy.

Despite its great successes, Newton's law of gravity is not correct. This was first recognized by Albert Einstein in 1905. At that time he had just formulated his special theory of relativity, and had discovered a logical incompatibility between it and Newtonian gravity. In order to remove that incompatibility, Einstein reformulated the laws of gravity during the period 1905 to 1915, emerging finally with his famous general theory of relativity.

General relativity, which is conceptually the most simple and beautiful of all the modern laws of physics, states that gravity is entirely a manifestation of the curvature of spacetime, and that the curvature is determined by the matter content of the Universe. Since 1905 a number of other relativistic theories of gravity have been proposed. However, most of them have been disproved by experiment; and all of them are less simple and beautiful than general relativity (except, perhaps, to their authors).

All of the competing relativistic theories of gravity agree that Newton's law should be accurate to within one part in a million throughout the solar system, and to within at least one part in a thousand in all stars that were studied by observational astronomers before 1968. (The pulsars are the post-1968 exception!) Consequently, astronomers and physicists have always used Newton's law of gravity with impunity.

-- Or almost always: Even near the turn of the century, a few observations of very high precision were able to detect the relativistic breakdown of Newtonian gravity: In the late nineteenth century astronomers were puzzled by the fact that the orbit of the planet Mercury deviates from a perfect ellipse by more than Newtonian theory could explain. There was an anomalous advance of the perihelion by 0.43 seconds of arc per year. Put differently, after 13 million trips around the sun, requiring three million earth years, Mercury will have passed through its perihelion (nearest approach to the sun) one time less than it should according to Newton. Einstein's general theory of relativity explained this nineteenth-century anomaly by predicting that the sun's gravity is slightly stronger, at close distances, than Newton's law predicts. Most other relativistic theories of gravity of the early twentieth century failed to explain Mercury's orbit quantitatively and were thus removed from the "competition" even before it started.

A second crucial proof of the breakdown in Newtonian gravity was the relativistic bending of light. Einstein's theory predicted that starlight passing near the limb of the sun should be deflected by 1.75 seconds of arc, whereas Newton's law predicted no deflection. Observations during the 1919 eclipse of the sun in Brazil, carried out by Sir Arthur Eddington and his British colleagues, brilliantly confirmed Einstein's prediction to an accuracy of about 20 percent. This dealt the final death blow to Newton's law and to most other relativistic theories of gravity.

PHENOMENA WHERE DEVIATIONS FROM NEWTONIAN GRAVITY ARE CRUCIAL

During the last two decades scientists have discovered an important new guiding principle for research and development: A new effect, that is barely discernable when first discovered, may dominate all other effects in yet-to-be-studied

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situations. Example: Stimulated emission of light, predicted by quantum theory in the 1920's and barely discernable in the experiments of the 1930's, became the basis for the masers and lasers of the 1950's and 1960's, and was discovered by radio astronomers in 1963 as the source of natural "OH radiation" from huge interstellar gas clouds.

In line with this new principle, astrophysicists have devoted moderate effort (several hundred man years; several hundred thousand dollars of computer time) during the last decade to theoretical studies of phenomena where relativistic gravitational effects might be important -- indeed, crucial! The payoff has been far greater than expected, thanks to close interaction with observational astronomy. Below is described some of the payoff, beginning at the cosmological scale (10 billion light years) and working down to the scale of superdense stars (10 kilometers):

1. We have known since Einstein's early work that, on the scale of the entire Universe ("cosmology") -- by contrast with the scale of stars and galaxies -- relativistic gravitational effects are so great that Newtonian theory is useless. Until the 1960's cosmology rested on a very weak observational basis; but this decade has seen enormous progress as a result of hand-in-hand cooperation between theorists and observers.

2. The discovery of quasistellar radio sources ("quasars") in 1963 created a revolution in the outlook of astronomers. We began to realize that the Universe is much more violent than we had thought! What could be the source of the violent output of the quasars? It was not clear -- and is still not clear -- that nuclear fission or fusion is powerful enough. The only energy sources more powerful, according to current theory, are matter-antimatter annihilation, and relativistic gravitational collapse. Both of these, in principle, can convert one hundred percent of the mass of an object into energy.

In the early stages of gravitational collapse the Newtonian theory of gravity is a good approximation, but in the crucial late stages it is useless; relativistic effects dominate. Theoretical studies using Einstein's general theory of relativity have increased our understanding of collapse ten-fold in the last decade and have created a foundation which might -- hopefully! -- help us to solve the puzzle of the quasar energy during the decade to come. These studies have also revealed bizarre predictions: When a collapsing object reaches its "gravitational radius" (3 kilometers for the sun; perhaps billions of kilometers for a quasar), it disappears from the outside Universe leaving behind a gravitating "black hole" in space. Subsequently matter can fall down the black hole, increasing its gravitational pull on other bodies; but no matter can ever escape from inside the black hole. The actual existence of black holes in the Universe has not yet been verified by astronomical observations.

3. The redshifts of the light from quasars have posed another deep puzzle for astronomers. The redshifts are probably cosmological in origin -- i.e., due to the expansion of the Universe, in which case the quasars are up to ten times as far away as the farthest galaxies that have been observed; the redshifts might be gravitational in origin -- i.e., due to the intense gravitational fields around quasars; or they might be doppler in origin -- i.e., due to the quasars having been ejected, with velocities nearly as great as light, from the interiors of galaxies near us. In all three cases relativistic deviations from Newtonian gravity are crucial: if the redshifts are cosmological or gravitational they are due entirely to relativistic deviations from Newtonian gravity; if they are doppler, then the ejection process probably entailed intense relativistic gravitational fields. Consequently, the quasars have not only stimulated further cosmological research; they have also stimulated theoretical studies of energetic objects with intense, fully relativistic gravitational fields (supermassive stars and superdense star clusters). Under close theoretical scrutiny, the cosmological explanation of redshifts has held up well, while the others have fared more poorly. For example, according to general relativity, when stars and star clusters have gravitational fields strong enough to produce the quasar redshifts, their gravity is more than strong enough to pull them into relativistic collapse and thereby convert them into black holes! There might be a few exceptions to this rule; but if so, the theoretical studies have not revealed them yet.

4. The supermassive stars, relativistic star clusters, and black holes which theoreticians have studied in connection with quasars, might also be important in the nuclei of galaxies: Since the late 1950's observational astronomers have known that violent explosions occur frequently (every few million years) in the nuclei of typical galaxies, and that in some special galaxies violent explosions may be almost an everyday occurrence. The causes of the explosions are unknown; in order to delineate them we need both additional observational data and deeper theoretical studies. It may be significant that conditions in the nuclei of galaxies are ripe for the formation of objects with relativistic gravitational fields, and that such gravity is capable of extreme violence.

5. Since the 1930's astrophysicists have pondered the question of what happens to stars after they have exhausted all of their nuclear fuel. Already by 1939 the rough outlines of an answer had been suggested by S. Chandrasekhar, by L. Landau, and by J. Robert Oppenheimer and his students: Stars less massive than 1.2 suns should contract to radii of a few thousand kilometers and become "white dwarfs" while more massive stars might collapse to radii of about 10 kilometers and become "neutron stars", or might undergo relativistic collapse, disappearing from the Universe and leaving behind "black holes" several kilometers in size. Very detailed theoretical studies during the last decade have agreed with these predictions, and have suggested that the collapse that forms a neutron star or a black hole might also produce the brilliant optical display that astronomers call a "supernova", and might produce outbursts of neutrinos and gravitational waves detectable at earth. These predictions are particularly intriguing because black holes and gravitational waves cannot exist according to Newtonian

gravitation theory; they are purely relativistic phenomena. And although neutron stars can exist in Newtonian theory, they should experience relativistic deviations from Newtonian gravity as great as 200 percent.

Detailed theoretical studies had delineated the key features to be expected of neutron stars, gravitational waves, and black holes by 1967; but there was no observational data to confirm or refute the theory. Then came two startling observational discoveries -- the detection in 1969 of what might be gravitational waves from the collapse that forms neutron stars and black holes (Joseph Weber, University of Maryland); and the discovery in 1967 of pulsating radio sources ("pulsars"), which are now believed to be rotating neutron stars. Without the theoretical studies of the last decade, we would have been totally unprepared for interpreting these two great discoveries. We might still believe, as did the radio astronomers who first discovered the pulsars and were unaware of most of the theory of superdense stars, that the pulsars are communication beacons of an advanced extraterrestrial civilization!

1970-80: THE DECADE FOR TESTING RELATIVISTIC GRAVITY

Astronomers and astrophysicists who have ignored relativistic theories of gravity until now, can no longer do so: Cosmology, quasars, the nuclei of galaxies, supernovae, pulsars and gravitational waves are all phenomena where relativistic deviations from Newtonian gravity may be crucial. But the scientist who wishes to include relativistic effects in his studies of these phenomena faces a dilemma: Which relativistic theory of gravity should he use? Most studies to date have used Einstein's general theory of relativity. But there are several other relativistic theories in competition with general relativity, which are compatible with all experiments to date.

Foremost among the other competing theories is the "scalar-tensor theory" due to Carl Brans and Robert H. Dicke (1961). Whereas general relativity (GRT) attributes all of the gravitational force to a curvature of spacetime, the Brans-Dicke theory (BDT) attributes 85 percent or more of it to spacetime curvature, and 15 percent or less to a scalar gravitational field similar to that of Newtonian theory. The ratio of curvature-produced gravity to scalar-field-produced gravity is called ω (omega) by Brans and Dicke. If ω is infinite, then BDT reduces to GRT; but if ω is finite, it does not.

In highly relativistic situations, where one is forced to use a relativistic theory of gravity, there are some very fundamental differences between BDT and GRT. For example, in BDT spherical pulsations of neutron stars should be halted after several seconds by the emission of scalar gravitational waves; but in GRT, where scalar waves are absent, a neutron star might pulsate spherically for many years. This difference could be very important for pulsars.

One might hope that the differences between the predictions of BDT, GRT, and other relativistic theories of gravity would be detectable in the observational data on pulsars, quasars, or cosmology. Unfortunately, there are so many non-gravitational effects that we do not understand influencing the observational data, that it may be hopeless in the next decade to weed out the effects of gravity. Astrophysicists would prefer to learn which theory is correct from solar-system experiments, and to then use that knowledge to interpret pulsars, quasars, and cosmology.

Relativistic gravitational effects are very small in the solar system -- less than one part in a million -- compared to pulsars, quasars, and cosmology, where they may be hundreds of percent. Nevertheless, in the solar system it is easier to disentangle the effects of gravity from other effects. Modern technology, including unmanned space craft, now makes it possible to do high-precision experiments which will distinguish between BDT, GRT, and other relativistic theories of gravity. By 1980 -- and probably much sooner -- we should have a number of tests which distinguish between the various theories to an accuracy greater than one part in a thousand. For example, if BDT is right, we should know by 1980 the value of its parameter ω; if GRT is right, we should know that ω is greater than 1000 -- large enough that the advocates of BDT will long since have given up.

All of the crucial experiments are extraterrestrial. Relativistic gravitational effects in an earthbound laboratory are too small to be measured -- except for the gravitational redshift, which was measured by Ezra Pound and his colleagues at Harvard University in 1963 to an accuracy of one percent, but which does not distinguish between the various relativistic theories. (Newtonian theory predicts no redshift and is thus incompatible with the experiment; all relativistic theories predict the same redshift and are thus indistinguishable.)

The following is a brief description of some of the crucial solar-system experiments that have been performed, are in progress, or are in the planning stages:

Experiments Using Optical Telescopes. Using optical telescopes one can perform two significant tests of relativistic gravity -- measurements of the deflection of light by the sun's gravity (1.75 seconds of arc at the limb of the sun according to GRT), and measurements of the relativistic shift in the perihelion of Mercury (0.43 seconds of arc per year according to GRT).

Until recently we thought that optical observations had verified the GRT perihelion shift of Mercury to two percent accuracy -- an accuracy sufficient to make $\omega > 30$ and thus convince us that BDT is probably wrong. However, two recent experiments reveal that the accuracy of the measurements was only ten percent, not two percent: (i) By studying the orbits of the planets with radar, American scientists have discovered that in many optical measurements of the solar system there are systematic errors ten times larger than the estimated errors. Such systematic errors might have been present also in the optical measurements of the perihelion shift.

(ii) Robert H. Dicke and Mark Goldenberg at Princeton University have discovered that the sun is optically oblate; its equatorial diameter is greater than its polar diameter by one part in 200,000. If the sun's gravitational field is oblate by a comparable amount, that oblateness could produce eight percent of the perihelion shift, thereby reducing the relativistic shift to 92 percent of its former value.

Fortunately, our new uncertainty about the perihelion shift can be resolved in the next few years using interplanetary radar and space probes (see below).

Let us turn attention to light deflection measurements. Until now the light deflection could be measured only during total solar eclipses. On an ordinary day the sun itself makes the sky so bright that, even with a coronograph in a telescope to blot out the sun's disk, one cannot see stars near the sun. This is unfortunate because total solar eclipses have the nasty habit of being very short and of occurring in the middle of oceans, jungles, and deserts, where good astronomical equipment is not normally available. These handicaps have made it impossible to measure the relativistic deflection of starlight with an accuracy of better than 20 percent.

Thanks to recent technological developments this is changing: Henry Hill of Connecticut Wesleyan University has developed electronic techniques for tracking stars as they move across the bright sky near the sun. Within one or two years he may be able to measure the relativistic deflection to an accuracy of one percent. His apparatus will also produce an independent measurement of the solar oblateness discovered by Dicke.

Experiments Using Trans-World Radio Interferometry. In the last few years Canadian and American radio astronomers have developed techniques for resolving radio sources on the sky with a precision as good as 0.0003 (i.e., 3×10^{-4}) seconds of arc. These techniques make use of trans-world interferometry: The radio waves from a given source are measured simultaneously using two radio telescopes on opposite sides of the world. The intensity of the radio waves as a function of time is put onto a magnetic tape by each telescope. The tapes are then brought together and compared by a computer. The data on the tapes are slightly different because the telescopes were so widely separated. By examining those differences, one can learn the size and shape of the source with very high precision. The measurements of the greatest precision (0.0003 seconds of arc) are those initiated in the autumn of 1969 with one telescope in the United States, and the other in the Soviet Union.

These same techniques can also be used to measure the angular separation between two distant radio sources. Of particular interest are the quasars 3C 279 and 3C 273, which are separated by 8 degrees on the sky. Each October the sun passes in front of 3C 279, as seen from earth. By measuring the separation of 3C 279 and 3C 273 as functions of time during that passage, one can see the deflection of 3C 279's radio waves by the sun's gravity. (This deflection should be the same as for light waves.) Such measurements using trans-world interferometry might yield the deflection to 3×10^{-4} seconds of arc accuracy during the 1970's -- an accuracy approaching one part in 10000 of the GRT prediction! Already the first such measurements, performed at Caltech and JPL in October 1969, have yielded a precision of about 5 percent (though the data are not yet fully analyzed).

It is fun to notice that, if in the future radio astronomers try to establish a high-precision coordinate system on the sky using trans-world interferometry, then as time passes their coordinates will bend and warp everywhere (not only near the sun) by about 0.01 seconds of arc, because of the sun's gravitational deflection of all radio waves.

Experiments Using Passive Radar. Another new tool for testing gravity is interplanetary radar: Radar waves are emitted into space by a huge transmitter; they travel across the solar system until they hit another planet; the planet reflects them; and the reflected waves then travel back to Earth, where they are received by a radio telescope. By measuring to high precision the round-trip travel time for such waves (i.e., the delay time between emission and reception), astronomers can determine with high precision the distance between Earth and the reflecting planet. Currently a precision of about 1 kilometer is possible in several hours of observing time.

Such precision is adequate to test several facets of relativistic gravity. For example, the relativistic perihelion shifts of Mercury, Venus, and Earth are now being measured by radar to a precision of about one percent by Irwin Shapiro of M.I.T.

Also, when radar waves pass near the sun, their round-trip travel time should be greater in GRT than in Newtonian theory, because in GRT they propagate through a curved space. The added relativistic delay is 0.0002 seconds out of a total delay of about 25 minutes for Earth-Venus-Earth travel -- or about one part in seven million. BDT predicts a relativistic delay shorter than this by up to 5 percent, depending on the value of ω. The relativistic delay was measured in 1968 for the first time, to an accuracy of 5 percent, by a team headed by Irwin Shapiro at the Lincoln Laboratory of the Massachusetts Institute of Technology. An experiment accurate to one percent may be performed soon using the Haystack transmitter of Lincoln Laboratory and the Goldstone receiver of Caltech's Jet Propulsion Laboratory. The added precision is possible because of the unprecedented sensitivity of the Goldstone receiver -- a sensitivity which was bought for the American space exploration program, but which cost much more than the radar- or radio-astronomy programs could have afforded!

Experiments Using Active Radar. There is little hope of achieving distance measurements better than one percent of the relativistic effects by using ordinary interplanetary radar. However, a different type of radar -- "active radar" -- promises to provide precision which is 100 times better during the

1970's.

In active radar the signal is not bounced off a planet; rather, it is received and retransmitted by a "transponding system", which is on board a space craft or has been landed on the surface of another planet. As with ordinary passive radar, one determines the distance between Earth and the transponder by measuring the round-trip travel time of the radio wave.

Active radar has been used to track American space craft since 1965. At present the precision obtained in several hours of measurement is about 10 meters (100 times better than with active radar!). Unfortunately, no data have been made public about Soviet passive-radar capabilities; we can only hope that they are similar to the American capabilities.

What tests of gravity can be performed using active radar? First of all, one can measure the relativistic time delay for signals passing near the sun. This will be done in May 1970 using transponders on board the two Mariner space craft which photographed Mars in September 1969. (This May these two craft will be on the far side of the sun.) This experiment should yield a one percent measurement of the relativistic delay; and similar experiments with other American space craft in 1971 and 1975 should give 0.1 percent precision or better.

The enormous precision (10 meters) of active radar makes it the ideal instrument by which to study the orbits of the planets in the solar system. By putting a transponder in orbit about a planet, or by landing one on its surface, scientists should be able to track the distance between the center of the Earth and the center of the planet to a precision of a few meters. The combined data from transponders around Mercury, Venus, Mars, and perhaps Jupiter would tell us in minute detail all of the orbital (and, hence, gravitational) properties of the inner part of the solar system.

Not only could we obtain perihelion shifts with precisions of 0.1 percent or better; we could see many other relativistic effects on the planetary orbits. For example, according to calculations by Kenneth Nordtvedt, BDT predicts that in a given external gravitational field the sun should fall more slowly than Mercury by one part in a million; Jupiter should fall more slowly by one part in a billion; and the Earth more slowly by one part in 10 billion. Put differently, the ratio of gravitational to inertial mass should be different for different planets. GRT predicts no such differences. As a result of these BDT differences, there should be an anomalous 100 meter deformation of the orbits of Earth and Mars, and this deformation should be dragged along by Jupiter as Jupiter moves around the sun. This anomalous deformation should be measurable using active radar -- and it is only one of many new effects to be searched for.

It is clear that active radar could be the most powerful and versatile tool of all for testing relativistic gravity in the 1970's. However, to put transponders around planets is very expensive; so the amount of data which we shall acquire will be limited. For this reason it is of the greatest importance that we combine together the Soviet and American transponder data on the time evolution of the distances between Earth and the other planets. Combining the data will enhance their value manyfold. Here is a great new opportunity for Soviet-American scientific cooperation!

Experiments Using Laser Ranging. For the special case of the Earth-moon separation a different type of passive radar is available: One can shoot a laser beam from the Earth to the moon, bounce it off the corner reflector which the Apollo 11 astronauts put there, and receive the reflected beam back at Earth. By measuring the round-trip travel time one can probably determine the Earth-moon separation to a precision of 6 cm. (Such experiments cannot be performed with other planets during the next decade, even if a corner reflector is put on them. A laser beam with sufficient power to reach out and back would probably damage the lenses and mirrors of the telescope used to transmit it.)

A 6-cm monitoring of the Earth-moon distance should enable astronomers to see relativistic gravitational effects of a totally new type: effects on the moon's orbit produced by the nonlinear superposition of the gravitational fields of Earth and sun. These effects, with magnitudes of 100 cm and less, will be different in different theories of gravity. The laser experiments should also test, with one to 10 percent accuracy, the BDT prediction that the accelerations of Earth and moon toward the sun differ by one part in 10 billion.

Gyroscope Experiments. C. W. F. Everitt and W. M. Fairbank of Stanford University are preparing an experiment to put four superconducting gyroscopes in a satellite in polar orbit around the earth. According to Newtonian theory these gyroscopes should always point at the fixed stars. However, relativistic theories of gravity predict that they should precess by about 7 seconds of arc per year due to the curvature of space induced by the Earth's mass, and by 0.05 seconds per year due to the curvature induced by the Earth's rotation. As for other solar-system experiments, so also here, BDT and GRT predict results which differ by about 5 percent or less. The expected precision of the experiment is 0.01 to 0.001 seconds of arc per year -- good enough to distinguish clearly between the theories. The experiment will be flown in about 1973.

CONCLUSION

One might ask: If so many different experiments promise to give high precision tests of relativistic gravity within the next few years, why should the money be spent to carry them all out? The answer is that each different type of test measures a different aspect of gravity. Until a large number of different aspects have been tested, we cannot pin down the correct relativistic theory with certainty. And having the correct theory will be crucial to future interpretations of the observational data from cosmology, quasars, pulsars, supernovae, and the nuclei of galaxies.

In retrospect, it is a remarkable tribute to Albert Einstein that, with essentially no observational data at his disposal, he was able to produce the general theory of relativity -- a theory which only now, 50 years later, is being recognized as an indispensible key to astronomical understanding. And it is a tribute to modern technology that we can at last test Einstein's theory of gravitation by using the extraterrestrial Universe as our laboratory.